FINAL REPORT

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HEAT TRANSFER CHARACTERISTICS OF SHS REACTIONS

K. V. Logan, G. R. Villalobos, J. N. Harris, P. Mackie, S. C. Neel and R. Frost
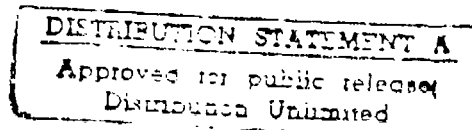
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Report for Period 1 October 1989 - 31 May 1990

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A Unit of the University System of Georgia
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The program consisted of two inter-related tasks: theoretical modeling and experimental verification.

Task I of the effort focused on thermodynamic modeling of the SHS reactions, and modeling of the heat transfer efficiency between the SHS reaction and the target plate. This task limited the number of acceptable reactions.

Task II consisted of verifying experimentally the results of Task I. During this stage, several reactions were initiated on fully instrumented target plates. Useful data of these reactions was collected using thermocouples, rLIR, and video recording. This data was analyzed in order to optimize the heat transfer of each reaction.

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A Unit of the University System of Georgia
Atlanta, Georgia 30332

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ABSTRACT

The objective of this program was to explore the exothermic properties of SHS reactions and the feasibility of using such reactions to melt through steel and brass plates.

The program was conducted under Contract No. DAALC3-89-K-0177 and consisted of two inter-related tasks: theoretical modeling and experimental verification.

Task I of the effort focused on thermodynamic modeling of the SHS reactions, and modeling of the heat transfer efficiency between the SHS reaction and the target plate. This task limited the number of acceptable reactions.

Task II consisted of verifying experimentally the results of Task I. During this stage, several reactions were initiated on fully instrumented target plates. Useful data of these reactions was collected using thermocouples, FLIR, and video recording. This data was analyzed in order to optimize the heat transfer of each reaction.

PREFACE

The research program was conducted under Contract No. DAAL03-89-K-0177 (Georgia Tech Project No. A-8500-000) with Dr. Andrew Crowson serving as the Contacting Officer's Technical Representative.

The program was conducted in two interrelated tasks:

- o Task I: Theoretical modeling and selection of possible SHS reactions.

- o Task II: Experimental verification and optimization of proposed SHS reactions.

The results of Task I and Task II are contained in this Final Technical Report.

The objectives of the program were as follows:

- o Task I: Using thermodynamic and heat transfer modeling to select possible SHS reactions which could achieve the program goals.

- o Task II: Reacting proposed SHS reactions on fully instrumented target plates to optimize efficiency of reactions through the use of moderators.

ACKNOWLEDGEMENTS

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INTRODUCTION

This Final Technical Report contains the results of Task I and Task II under Contract No. DAAL03-89-K-0177 (GTRI Project No. A-8500-000) during the period 1 October 1989 to 31 May 1990.

The program was divided into two inter-related tasks; theoretical modeling, and experimental verification and optimization. The theoretical modeling portion of the program was further subdivided into thermodynamic modeling of the SHS reactions, and modeling of the heat transfer efficiency between the SHS reaction and the target plates. The theoretical models were verified experimentally by reacting selected SHS reactions on fully instrumented target plates. Of major concern during verification was the actual temperatures reached by the reaction and the heat transfer efficiency between the reaction and the plate. For comparison, the mass of the SHS precursor powder mix and the mass of the target plate must be maintained constant. Comparing different powder to plate weight ratios provided no significant insight into the relative performance of two different reactions. Results from SHS reactions served to further refine the theoretical modeling.

BACKGROUND

Due to the infinite number of possible SHS reactions it was necessary to develop a theoretical basis for quickly selecting reactions which could possibly accomplish the intended task. Theoretical selection was divided into two parts; modeling of the reactions themselves and modeling the interaction between the

reaction and the metal plates.

The adiabatic temperature of the proposed reactions (Table I) was calculated using the equation:

$$H_{rxn} (298 \text{ K}) = \text{sum } [n_{i*}(Cp_s(i,T)dT + Cp_l(i,T)dT + H_{fus(i)})] \quad (1)$$

where $C_{ps}(i,T)$ and $C_p l(i,T)$ are the specific heats of the ith product of the solid and liquid phases respectively, at temperature T; $H_{fus}(i)$ is the heat of fusion for the ith product, and the summation is over all product species. Since the integral of the heat capacity from T_1 to T_2 is simply the enthalpy difference between these two temperatures, it is easier to use enthalpy tables than C_p data. Reactions were initially chosen based on high adiabatic temperatures.

Knowledge of the adiabatic temperature and vaporization point of the product materials allows reasonable predictions as to the relative violence of the reaction in question. If the adiabatic temperature was above the vaporization point of a product material a violent explosion was a possibility. This information was crucial in determining whether a reaction should be moderated through addition of a non reacting component. Moderation proceeded through a theoretical and experimental analysis to determine the best type of moderator, metal or ceramic, and the optimum amount of moderator to use.

Most high temperature combustion reactions are exothermic. Ignition of the loose powder in stoichiometric amounts usually

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TABLE I. Proposed Reactions.

Reaction	Adiabatic Temp. (K)	kJ/g
$MoO_3 + 3Ca \longrightarrow Mo + 3CaO$	4500	4.39
$MoO_3 + 3Mg \longrightarrow Mo + 3MgO$	4100	4.90
$MoO_3 + 3Sr \longrightarrow Mo + 3SrO$	3800	2.53
$MoO_3 + 2Al \longrightarrow Mo + Al_2O_3$	4300	4.70
$WO_3 + 3Ca \longrightarrow W + 3CaO$	4000	3.02
$WO_3 + 3Mg \longrightarrow W + 3MgO$	3700	3.15
$WO_3 + 3Sr \longrightarrow W + 3SrO$	3680	1.89
$WO_3 + 2Al \longrightarrow W + Al_2O_3$	3900	2.66
$Fe_2O_3 + 2Al \longrightarrow 2Fe + Al_2O_3$	3135	3.97

results in a violent, often explosive reaction. Explosive behavior is caused by the vaporization of impurities or reaction products.

The reaction can be made less violent by the addition of a moderating material. However, as the amount of moderator becomes high compared to the amount of reactant, the reactants may become isolated and competing reactions between the reactants and moderator may predominate. This problem can be overcome by using one of the reactant or product materials as the moderator.

The amount of material needed to melt a unit mass of steel or brass under adiabatic conditions can be predicted by determining the weight of a 1 inch diameter by 0.25 inch thick steel or brass charge and multiplying by the heat of fusion in kJ/g. The heat of fusion obtained is used to calculate the weight of reactants needed to supply the required energy.

Theoretical reaction modeling provided a good picture of the ultimate efficiency of the system under consideration; however, it did not take into account the various heat loss mechanisms present in actual practice. Modeling of the physical interaction between the SHS reaction and the metal plates provided the necessary second step in selection of candidate material systems. The theoretical heat transfer analysis was done using the Martin Marietta Interactive Thermal Analysis System (MITAS). MITAS uses four different types of nodes (diffusion, arithmetic, boundary, and heater) connected by four different types of connectors (conduction, convection, radiation, and fluid flow) to predict a temperature-time profile. A "mesh" of nodes and conductors is defined by the user to simulate the geometry of the problem. A

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finite element analysis technique evaluates the mesh. The nodes
have a heat capacitance given by:

$$\text{Capacitance} = \text{Volume X Density X Specific Heat} \quad (2)$$

The heat transfer through the conductors is similarly given by (3)
for conductive heat transfer and (4) for radiative heat transfer:

$$\text{Heat} = -(\text{k X Area X Delta Temperature}) / \text{Length} \quad (3)$$
$$\text{Heat} = \text{GBF X Area X e X Delta Temperature}^4 \quad (4)$$

where k is the thermal conductivity, GBF is the grey body factor,
and e is the Stefan Boltzmann constant. The MITAS program
evaluates each node based on the conditions of the neighboring
nodes and conductors at time intervals of 0.04 minutes. Steady
state boundary conditions are applied to determine the temperature
at infinite time. Figure 1 shows geometry of the plates evaluated,
and the nodes and conductors that were defined. The nodes are
labeled in circles above their positions, while the conductors are
labeled above their appropriate path. Data for MITAS was provided
by a series of experimental SHS reactions on instrumented metal
plates. In this manner actual values of radiative and convectional
losses were programed into MITAS. Further experimental reactions
provided information on the relative efficiency of heat trans-
mission between the reaction and the metal plates. Experimental
verification of the MITAS heat transfer model showed good
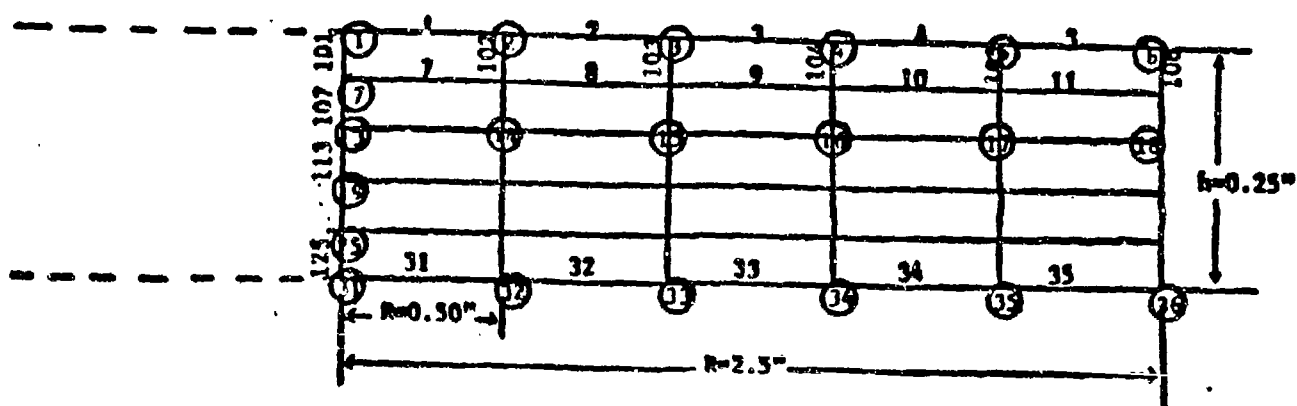correlation between the models and actual reactions.

Figure 1.   MITAS Node and Connector Map.

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TECHNICAL APPROACH

Experimental reactions were used to verify and optimize the theoretical models, and to provide concrete data for the models. Theoretically unacceptable reactions were both randomly and selectively chosen to ascertain the efficiency of the theoretical selection process. Initially, the reactions were used to provide data and optimize the theoretical models. The set up for the data gathering stage consisted of 5 inch diameter by 0.25 inch thick plates instrumented with 9 type K thermocouples, Figure 2. Verification consisted of a five step process designed to quickly screen unacceptable material systems. Plates used for verification were 1 inch squares with thicknesses ranging from 0.0625 to 0.25 inch.

EXPERIMENTAL SET UP

Data gathering and optimization.

Initial experimental runs were performed to gather data to be used in heat transfer modeling. It was necessary to obtain maximum and minimum values of the heat transfer efficiency across the reaction/plate interface, and radiative loss from the reaction and plate. Additionally, some of the heat radiated from the reaction was recovered on the plate in the immediate vicinity of the reaction. Several iterations of the modeling/verification process were needed to obtain meaningful information from the model.

Steel and brass plates were used in this phase of the investigation. The plates were 5 inches in diameter and 0.25 inch thick. A total of 9 type K thermocouples were swaged into each
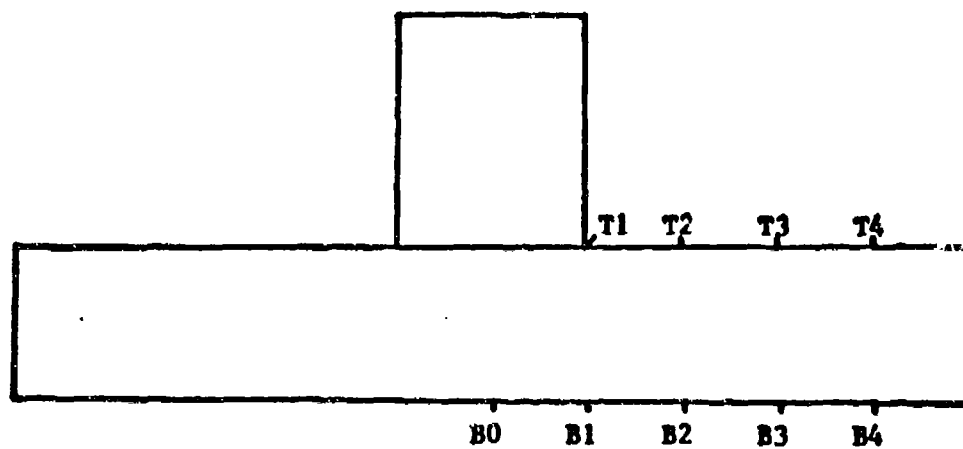
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Figure 2. Thermocouple Location and Designation.

plate. The thermocouples were located radially 0.50 inch apart with their respective leads 0.25 inch apart, Figure 3. The leads ·ere placed apart instead of in a bead to obtain an average of the temperature.

Temperature data obtained from the thermocouples was confirmed by FLIR (Forward Looking Infra-Red) recording of the reactions in progress, Figure 4. The FLIR provides a complete mapping of the temperature distribution throughout the entire plate. However, only those points roughly corresponding to the thermocouple placements were analyzed. Figure 5 shows the complete set up used in the first phase of the program. The figure is not to scale.

Verification of theoretical selections.

Systems selected through theoretical modeling were tested in a five step process, Figure 6. The process allowed for early identification of unsuitable SHS systems, reduced the cost of materials, and minimized the risk inherent in untried SHS reactions. In steps one and two the reaction was optimized for maximum heat flux delivery to the bottom of the silica crucible. Dilution of the SHS reaction with either a metallic or ceramic component, moderator, permitted the use of violent reactions possessing desirable characteristics. Steps three and four determined the heat flux delivered to a 0.25 inch thick plate. Step five was randomly used to verify the theoretical selection process. SHS systems satisfactorily completing the five step test were scaled up to 200 grams and reacted in the set up shown in Figure 7. The reactions were judged on the number of plates
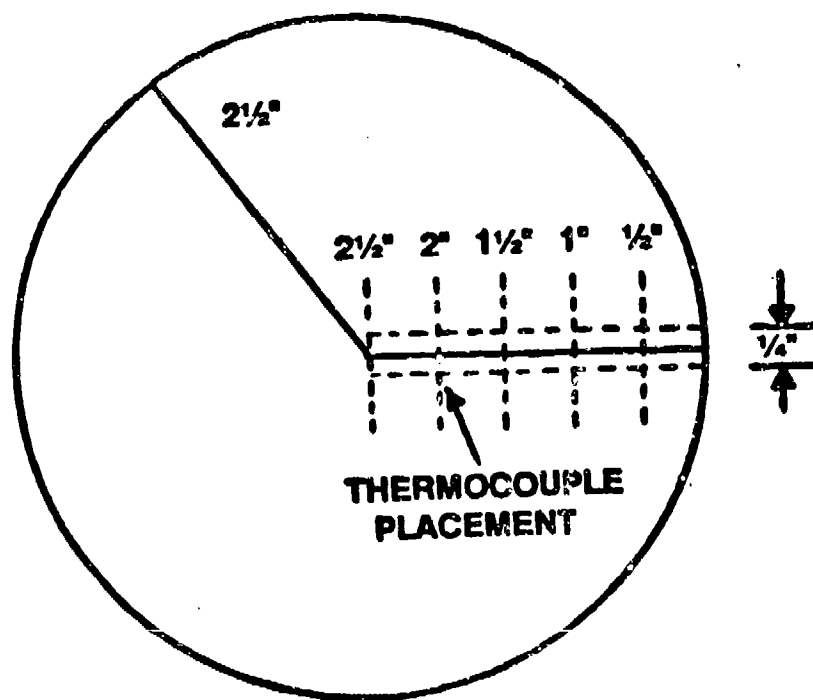
Figure 3.   Thermocouple Locations.
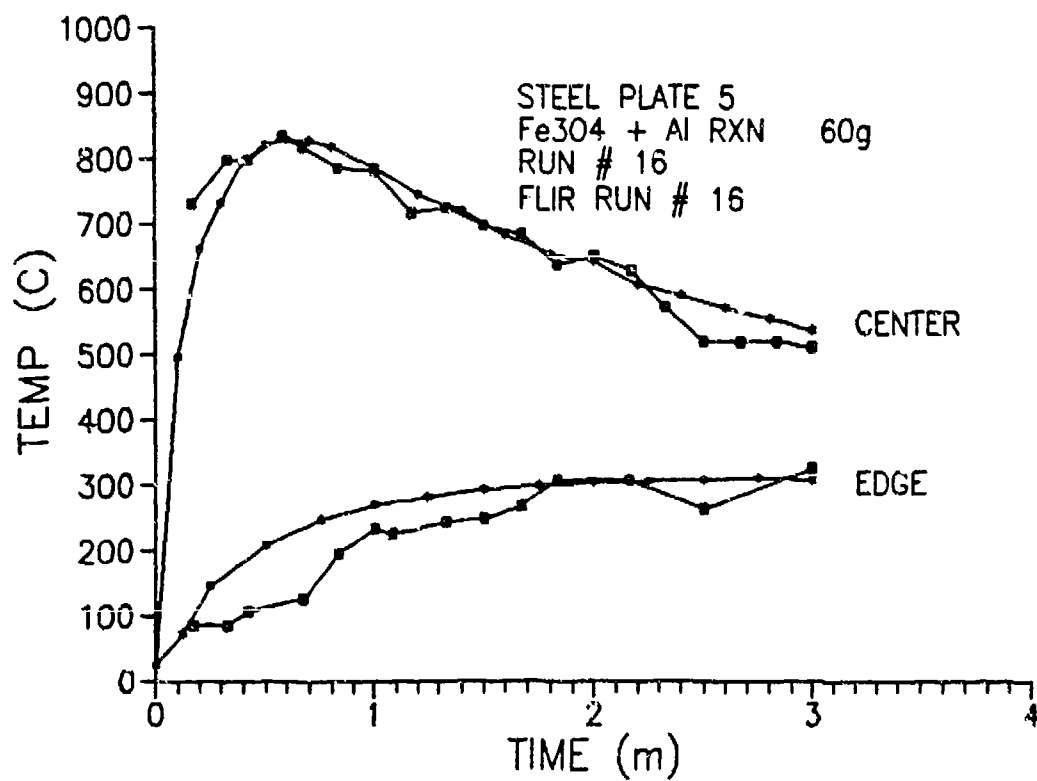
Figure 4. FLIR/Thermocouple Comparison.

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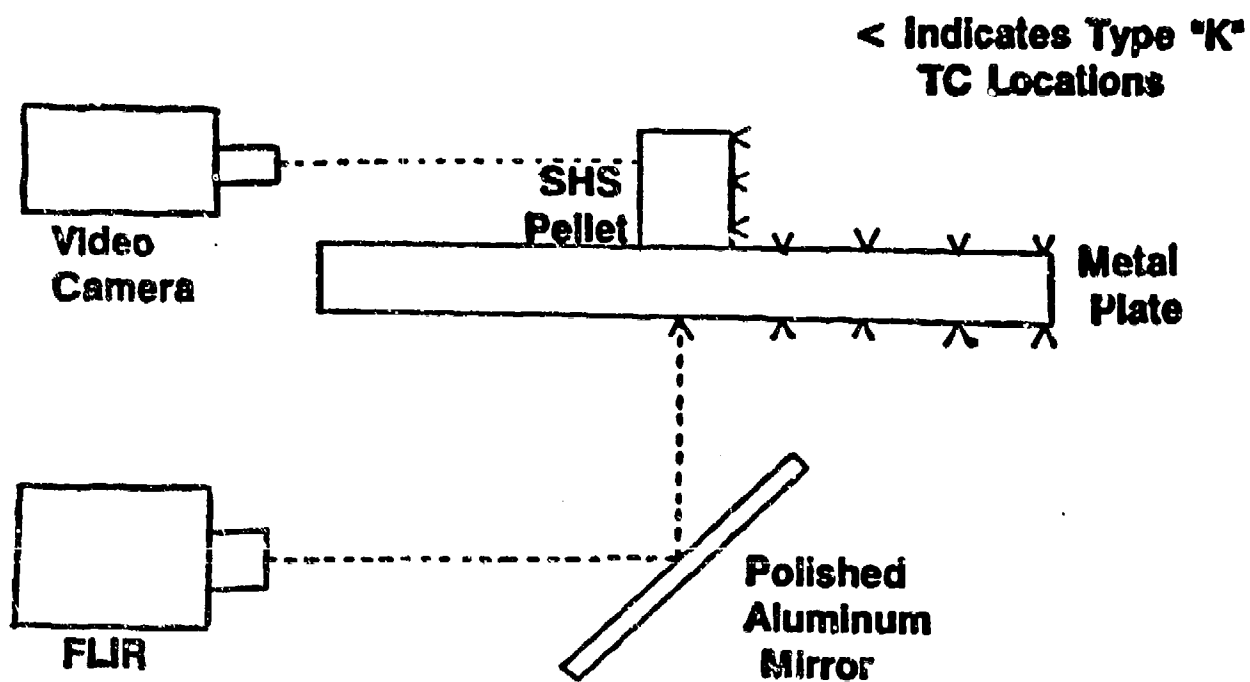
Figure 5. Experimental Set Up.

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o 10g Unmoderated Precursor Material Reacted in a Silica Crucible

o 10g Precursor Material Progressively Diluted Until Controlled Burn Obtained

o 25g Diluted Material Reacted on 1" Square Steel Place

o 60g Diluted Material Reacted on Steel and Brass Reaction Plates

o Thermocouple Data Recorded and Plotted

Figure 6.   Five Step Experimental Approach.

SILICA TUBE

PRECURSOR
POWDER MIX

CONTAINMENT
RING
TEST PLATE

CONTAINMENT
RING
TEST PLATE

LEFT SUPPORT
(RIGHT SUPPORT NOT SHOWN)
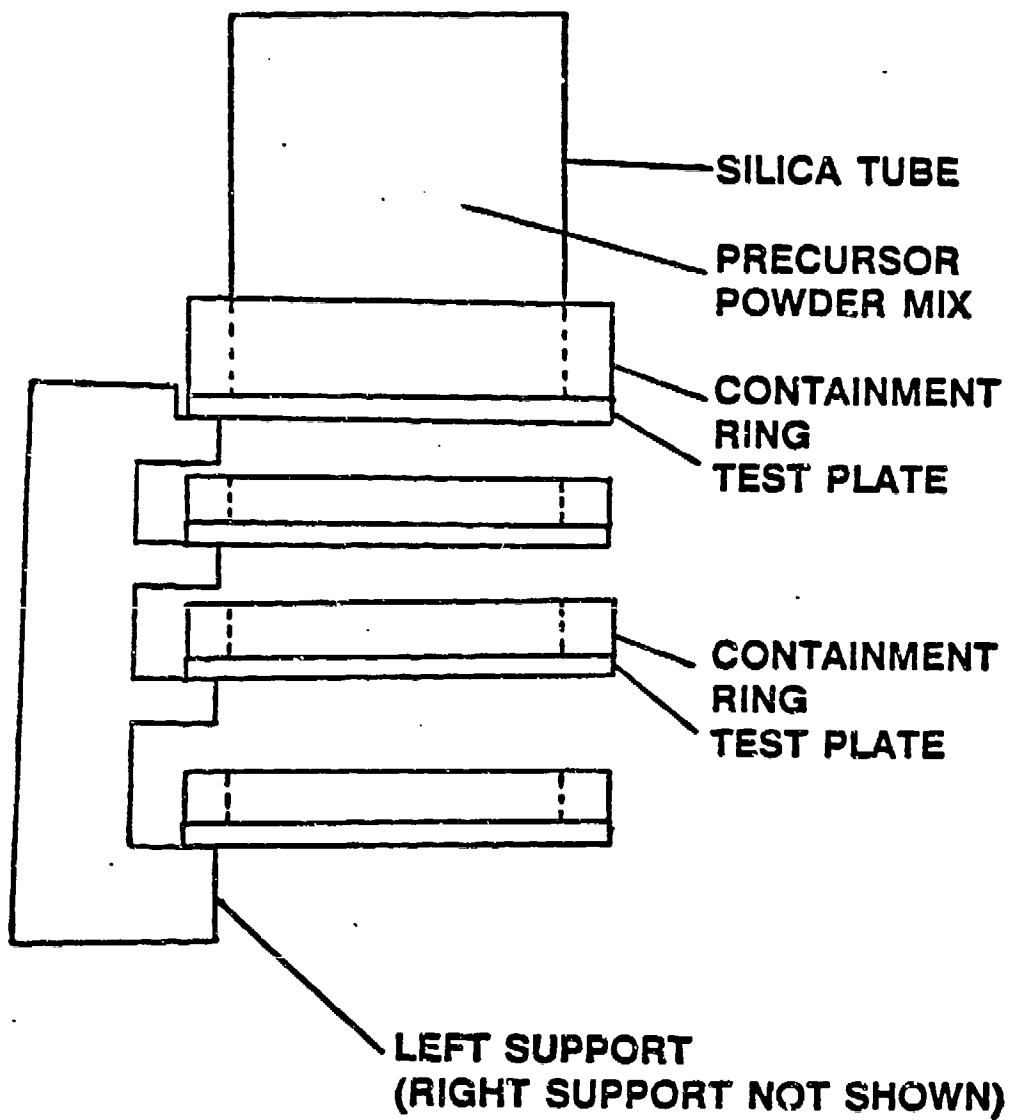
Figure 7. Multi-plate Set Up.

successfully burned through using a 200 gram mass of precursor powder.

Moderators where initially chosen solely for their ability to absorb heat and thus reduce the violence of the reaction. Later experiments used the moderator as part of the heat transfer system. Moderator fractions are listed in Table II.

TABLE II. Reaction Moderation.

Moderated

- 20 Wt % Al_2O_3
- 30 Wt % Al_2O_3
- 40 Wt % Al_2O_3

Moderated

- 20 Wt % SiO_2
- 30 Wt % SiO_2
- 40 Wt % SiO_2

Moderated

- 50 Wt % Fe
- 100 Wt % Fe
- 150 Wt % Fe
- 200 Wt % Fe

RESULTS

The results are divided into to two sections; results of the theoretical modeling, and results from the experimental effort. The SHS theoretical selection model was concerned with reactions possessing high reaction temperatures and heat capacities, high oxide heat of formation for all reaction products, and good thermal conductivity. The heat transfer model was concerned with the efficiency of the heat transport across the reaction/plate interface, conduction through the plate, and radiative heat losses from the plate and reaction. Experimental results include the relative heat transfer efficiencies of the different type of reaction products, metal/oxygen ratio of the precursor oxide materials, and product solidification temperature.

THEORETICAL MODELING

Reaction modeling.

Table III shows the enthalpy of various reactions considered in the program, Table IV shows the adiabatic temperature of the reactions, and Table V gives melting and vaporization temperatures for the reactants. By studying Table V the theoretically best reactants were chosen and their reactions are shown in Table IV. Table IV gives adiabatic temperatures and heat production per gram of each of the chosen reactions. From this data the choices were narrowed to reactions 1, 2, 4, 5, 8, 9. These reactions all achieve complete melting with little vaporization --- ideal parameters.

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TABLE III. Thermodynamic Data of Various Oxide Species
(units are kJ/mol unless otherwise specified).

Oxide	ΔH_f	ΔH_f/O atom	ΔH_{fus}	ΔH_{fus}/O atom	T_{fus}(K)
CaO	-635.1	-635.1	80.5	80.5	3200
MgO	-601.2	-601.2	78.1	78.1	3105
Li_2O	-598.7	-598.7	58.4	58.4	1843
SrO	-592.0	-592.0	65.0	65.0	2938
Al_2O_3	-1675.7	-558.6	78.5	26.2 .	2327
ZrO_2	-1097.5	-548.8	87.0	43.5	2950
UO_2	-1085.	-542.5			
TiO_2	-944.7	-472.3	66.9	33.4	2130
SiO_2	-902.66	-451.3	9.58	4.79	1700
U_3O_8	-3569.3	-446.2			
VO	-431.8	-431.8	64.3	64.3	2063
B_2O_3	-1271.9	-424.0	24.07	8.02	723
NbO	-419.7	-419.7	85.5	85.5	2210
Na_2O	-417.9	-417.9			
Ta_2O_5	-2046.0	-409.2	120.1	24.02	2058
NbO_2	-795.0	-397.5	92.0	46.0	2175
Nb_2O_5	-1899.5	-379.9	104.5	20.9	1785
Cr_2O_3	-1134.7	-378.2	29.7	43.2	2603
K_2O	-363.2	-363.2	Decomposes	---	1154
Li_2O_2	-632.2	-316.1	Decomposes	---	468
V_2O_5	-1550.6	-310.1	64.5	12.9	943
P_4O_{10}	-3009.9	-301.0	Sublimes at 630 K		
WO_2	-589.7	-294.9			
MoO_2	-587.9	-293.9	?		>3000
WO_3	-842.9	-281.0			
Fe_2O_3	-825.5	-275.2	Decomposes		
FeO	-272.0	-272.0	24.1	24.1	1650
$AlBO_2$	-541.4	-270.2			
Na_2O_2	-513.2	-256.6			
MoO_3	-745.2	-248.4	47.0	15.7	1074
NiO	-240.7	-240.7			
K_2O_2	-459.8	-229.9	Unknown		763
CuO	-156.8	-156.8	11.8	11.8	1720

TABLE IV. Adiabatic Temperature of Selected Reactions.

Reaction	Addiabatic Temp. (K)	kJ/g
$MoO_3 + 3Ca \longrightarrow Mo + 3CaO$	4500	4.39
$MoO_3 + 3Mg \longrightarrow Mo + 3MgO$	4100	4.90
$MoO_3 + 3Sr \longrightarrow Mo + 3SrO$	3800	2.53
$MoO_3 + 2Al \longrightarrow Mo + Al_2O_3$	4300	4.70
$WO_3 + 3Ca \longrightarrow W + 3CaO$	4000	3.02
$WO_3 + 3Mg \longrightarrow W + 3MgO$	3700	3.15
$WO_3 + 3Sr \longrightarrow W + 3SrO$	3680	1.89
$WO_3 + 2Al \longrightarrow W + Al_2O_3$	3900	2.66
$Fe_2O_3 + 2Al \longrightarrow 2Fe + Al_2O_3$	3135	3.97

TABLE V. Melting and Boiling Temperatures of the Common Metals.

Metal	MW.	T_m(K)	T_{vap}(K)
Li	6.9	453	
Na	23.0	371	1171
K	39.1	337	1039
Be	9.0	1550	2757
Mg	24.3	922	1363
Ca	40.0	1111	1757
Sr	87.6	1043	1650
Ba	137.3	998	2171
Sc	45.0	1812	3104
Y	88.9	1796	3611
Ti	47.9	1932	3631
Zr	91.2	2125	4703
Hf	178.5	2495	4876
V	50.9	2163	3682
Nb	92.9	2741	
Ta	180.9	3287	5731
Cr	52.0	2130	2945
Mo	95.9	2890	4919
W	183.8	3683	>6000
Mn	54.9	1518	2335
Fe	55.8	1808	3135
Co	58.9	1768	3201
Ni	58.7	1726	3187
Pd	106.4	1825	3237
Pt	195.1	2045	
Cu	63.6	1356	2848
Zn	66.4	693	1180
Al	27.0	933	2767

A typical steel plate weighs 25.3 grams, and the heat of fusion for iron is 1.07 kJ/g. Therefore, the heat required to melt a steel plate is 25.3 * 1.07 = 27.1 kJ. By similar calculation, the brass plate requires 10.2 kJ to melt. Table VI lists the amount of reactant needed to supply the correct amount of heat to melt a plate.

Moderation.

Figure 8 shows the effect of aluminum and iron moderators on the theoretical adiabatic temperature of the Fe_2O_3/Al reaction. The horizontal lines are the location of phase changes. Since the maximum reaction temperature must be below the vaporization of the reaction materials, the minimum amount of aluminum moderation is 23%, and the minimum for iron is 15%. Figure 9 shows similar information for the aluminum and molybdenum moderation of the MoO_3/Al reaction. However, the low vaporization point of aluminum severely decreases the adiabatic temperature of the reaction.

EXPERIMENTAL RESULTS

Reaction product type.

Tested SHS reactions produced products ranging from molten metals and ceramics to friable sponge like structures. In general, the friable structures delivered approximately 10% of the total heat generated to the plate. Most of the heat was lost to the atmosphere through radiation and convection. Attempts to reduce losses with insulation slightly increased efficiency, however,
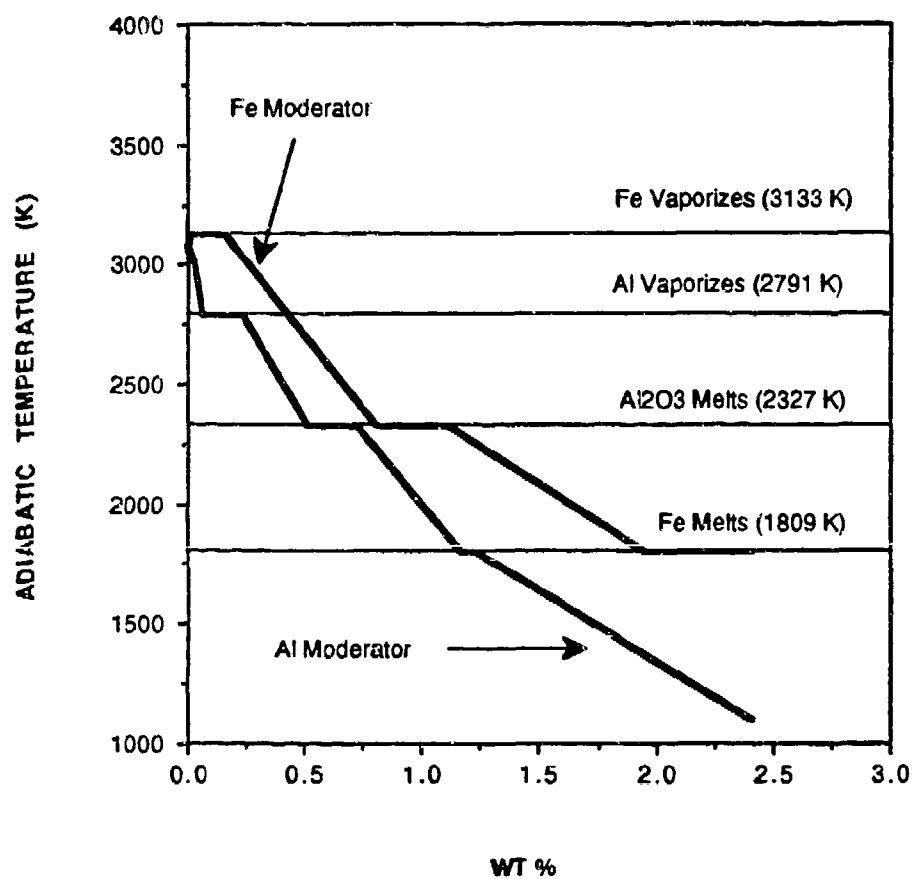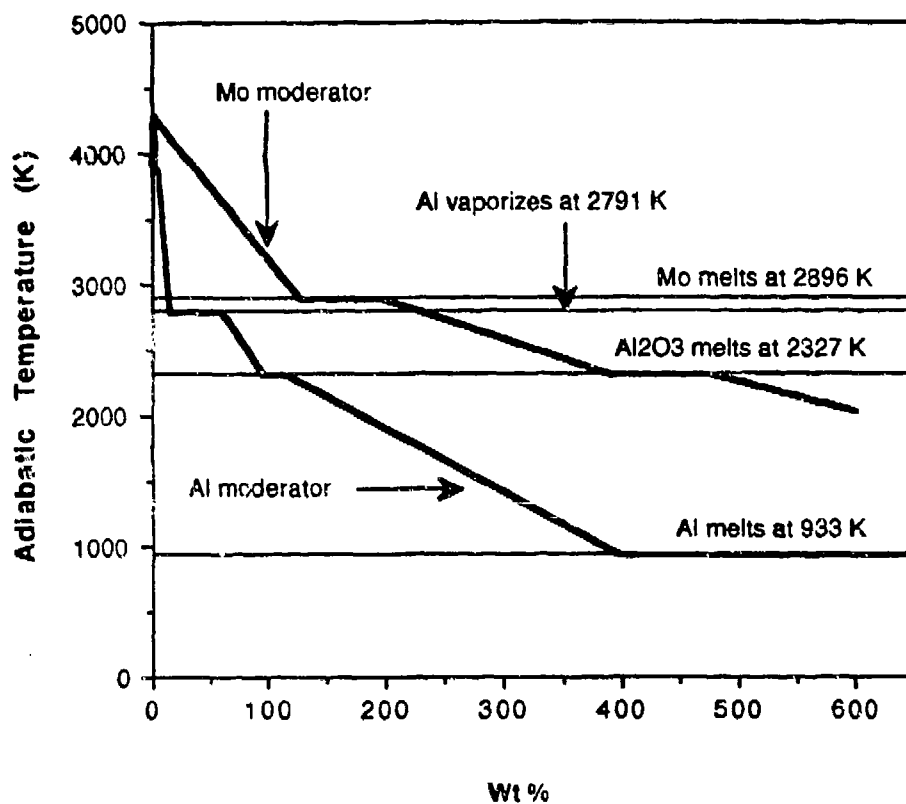
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Figure 8.   Effect of Al and Fe Moderators.

Figure 9.   Effect of Al and Mo Moderators.

TABLE VI. Grams of Precursor Material to Melt Steel or Brass.

Reaction	g to melt steel	g to melt brass
$MoO_3 + 3Ca \longrightarrow Mo + 3CaO$	5.9	3.6
$MoO_3 + 3Mg \longrightarrow Mo + 3MgO$	5.3	3.2
$MoO_3 + 3Sr \longrightarrow Mo + 3SrO$	10.3	6.2
$MoO_3 + 2Al \longrightarrow Mo + Al_2O_3$	6.3	3.8
$WO_3 + 3Ca \longrightarrow W + 3CaO$	8.6	5.2
$WO_3 + 3Mg \longrightarrow W + 3MgO$	8.3	5.1
$WO_3 + 3Sr \longrightarrow W + 3SrO$	13.8	8.4
$WO_3 + 2Al \longrightarrow W + Al_2O_3$	9.8	6.0
$Fe_2O_3 + 2Al \longrightarrow 2Fe + Al_2O_3$	6.5	3.7

maximum efficiencies remained under 20%. Molten products delivered up to 50% of the heat generated to the plate.

Precursor metal/oxygen ratio.

The metal to oxygen ratio of precursor materials greatly effected the amount of heat delivered to the metal plate when using molten metal type reactions. High metal/oxygen ratios formed the largest amount of molten metal product and therefore, delivered the greatest amount of the total heat generated to the plate. No effect was noted for systems producing friable product materials.

Product solidification temperature.

Product materials with low melting temperatures tended to deliver a greater total amount of heat to the target plate. However, if the low melting temperature product also possessed a vaporization temperature below the maximum reaction temperature, the reaction was explosive. Additionally, low melting temperature reaction generally produced less total heat. Optimum results were obtained when the melting temperature of the molten species was comparable to the melting temperature of the target plate.

Type of moderator.

The greatest amount of heat transfer was obtained when the moderator complemented the effect of the molten metal reaction product. The moderator should have a similar melting temperature to the molten product material. Metallic moderators performed better than ceramic moderators. Degree of heat delivery achieved

a maximum at specific dilution levels. Higher or lower dilution levels than optimum tended to decrease the heat transfer efficiency.

DISCUSSION OF RESULTS

THEORETICAL RESULTS

Discussion of reaction modeling.

Table IV gives the pertinent data for theoretical reaction choice. As mentioned previously, reactions 1, 2, 4, 5, 8, 9 are ideal candidates given their adiabatic temperatures and degree of melting. Of the above six reactions, the most desirable product for melting through a plate would be tungsten. The density of tungsten is so high that molten tungsten would easily melt the steel plate and its weight would pull it through the plate thickness. Molybdenum would be the second choice because its density and melting temperature are higher than steel. The iron reaction is near its vaporization point but with molten iron on iron the temperature gradient is so minute that melting of the solid steel might require more energy than the temperature gradient supplies.

When determining the amount of reactant needed to produce the required heat of fusion (Table VI), heat losses due to conduction, convection, and radiation are not taken into account. To obtain realistic data, the heat loss need to be taken into account.

EXPERIMENTAL RESULTS

Reaction product type.

Reactions which produced a friable product exhibited a localized transient heat which tended to lose the majority of its energy to the atmosphere. The high reaction temperatures generated

were insulated from the target plate by: the reaction product, in the case of ignition from the plate surface, or by the precursor powder mix. Most of the heat was carried away from the plate by the heated atmospheric gasses, the target plate received approximately 10% of the heat generated. Insulating the reaction crucible and directing the escaping gasses toward the plate somewhat increase the heat transfer efficiency to 20%, however, efficiencies of the friable component reactions never equaled the efficiencies obtained by the molten metal reactions.

Reactions which produced molten reaction products transferred up to 50% of the heat generated to the target plate. Most of the heat was stored in the molten product as the reaction proceeded. The molten metal, possessing a higher specific gravity than the precursor powder, tended to sink through unreacted precursor powder and come in contact with the plate. Heat from reaction was stored in the molten metal and transferred to the plate during the reaction and for several seconds after the reaction terminated. It was the longer heat residence time on the target plate in combination with the more efficient metal/metal interface which accounted for the improved heat transfer efficiency of the molten product reactions.

It should be noted that when more precursor powder was used, more molten metal was produced. This implies that more heat comes in contact with the steel or brass plate allowing for melt-through of thicker plates. In other words, if 25 grams of precursor powder is used, a plate .0625 inches thick might be melted through. If 1000 grams of precursor powder is used, a plate .5 inches thick

might be melted through. Therefore, equal weight reactions can be commpared but reactions using different amounts of precursor powder cannot be compared equally.

Precursor metal/oxygen ratios.

Reactions which produce friable reaction products have no heat storing mechanisms and therefore, the stoichiometry of the precursor materials have no great effect in the heat transfer efficiency. Reactions which produce molten products, however, are capable of storing large portions of the heat generated in the molten products. It is therefore desirable to have large quantities of molten products present. Unfortunately, ceramic materials are insulating and do not readily transfer their stored heat to surrounding materials. So to obtain the best possible heat transfer it is necessary to maximize the molten metallic products while minimizing the molten ceramic products. This can be accomplished by using precursor materials possessing high metal to oxygen ratios.

Product solidification temperature.

Optimum heat transfer efficiency is obtained from a molten metal/plate interface due to the more intimate contact between the molten and solid phases. When the molten metal solidifies, the degree of contact across the interface is reduced and heat transfer efficiency is degraded. However, low melting temperature metals generally posses low vaporization temperatures. If the temperature

generated by the reaction is in excess of the vaporization temperature the reaction will become explosive.

Type of moderator.

The moderator is introduced to a reaction to decrease the maximum temperature reached by the reaction. It prevents vaporization of constituent reaction materials and consequently prevents the reaction from behaving explosively. Although both ceramics and metals can be used as moderators, for the purpose of maximum heat transfer it is desirable to use metallic moderators. As discussed above, molten metals are more efficient in transferring heat to their surroundings than molten ceramics. The moderator can be used in conjunction with a molten metal product to store heat and deliver it to the target plate.

CONCLUSIONS

Documented physical and thermodynamic properties can be used to select SHS reactions possessing the desired properties. Heat transfer modeling can further refine the selection process by estimating the efficiency of the reaction/plate interaction. Generally, there is good agreement between the theoretical model and the experimental results. Experimental results have greatly narrowed the selection criteria for suitable SHS reactions. The reaction must posses a metal/oxygen ratio approaching one, molten metal products have higher heat transfer efficiencies than reactions which form friable products, metallic moderators decrease the reaction rate to optimum levels while aiding in heat storage and transfer.

RECOMMENDATIONS

The groundwork for a detailed analysis has been preformed. The infinite number of possible reactions has been narrowed to a manageable number. Future research should be aimed to maximizing the heat storage and delivery capabilities of the SHS reaction molten metal products.

Reactions to be considered in future work should only include those which posses a precursor metal to oxygen ratio near unity thereby producing large amounts of heat storing molten metal product while minimizing the amount of insulating ceramic phase.

Moderators should be chosen in such a way that they enhance the heat delivery capacity of the reaction without greatly decreasing the maximum reaction temperature. Low vaporization point product metals and moderators should be avoided.

Theoretical analysis must be an integral part of the reaction selection process. Accurate modeling greatly reduces the time necessary to eliminate large numbers of unsatisfactory systems.